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CONCEPTUAL DESIGN AND SIMULATION OF AFRICAN OIL BEAN SEED DEHULLER

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Abstract

Dehulling is a unit operation preceding oil extraction of most agricultural products. While it is common to dehull the African oil bean seed manually, the mechanical operation of the process has not been reported. Thus, this study was undertaken to design and simulate African oil bean seed dehulling machine. The design was based on previous investigation of the physical and mechanical properties of the seed at 15 % moisture content (db), including average breaking force of the seed (1.12 kN). Computational fluid dynamic method was used to carry out machine simulation and the effect of time of machine operation on motor torque; angular velocity and linear displacement were investigated. The design results show that a 3 HP, single phase electric motor was required to power 25 mm shaft diameter of the machine. The simulation results show that the angular velocity was high as soon as the machine commences operation, but this progressively decreases with an increase in the time of operation. The reason for this may be due to a decrease in the viscous effect of the internal wall which causes the air stream flow to slow down with a resultant drop in the relative angular velocity to the surface. This implies that the machine is practicable with performance likely to decrease with time of machine operation.

Keyword: African oil bean seed, Design, Simulation, Dehuller

1. Introduction

African oil bean (*Pentaclethra macrophylla*) is a tropical tree belonging to the family of *Leguminosae minosoadeae* and is popularly grown in Nigeria. The tree grows to a height of 21 m and is well branched and forms a crown like canopy. Flowering is by cross pollination, which is normally between March and November. The flowers produced by the plant are yellow and pinkish white in color, sweet smelling and attract myriads of insects including the honeybee. The plant bears fruit in the form of green pods which slowly darken with maturity and is 0.36 to 0.46 m long and 0.05 to 0.10 m broad. Each pod contains up to 10 seeds, and the pods split open to scatter the seeds up to a distance 20 m from the tree at maturity after harvest (Akindahunsi et al., 2004). The seeds are flat in shape, hard, but smooth in texture, brown in color and about 0.06 m long, as shown Figure 1 (Adekunle *et al*., 2008). Also, fermented product of the seeds is good delicacy in Nigeria due to its high nutritional composition (Akindahunsi *et al.,* 2004; Kar and Okechukwu, 1990). For instance, it is an important and cheap source of protein for people whose staple foods are deficient in protein and can be used as a flavor in soup.

Figure 1: Ruptured pod and seeds of African oil bean

Manual dehulling of the African oil bean seeds from the pods comes with some challenges. Adekunle *et al. (*2008) reported that the manual process of dehulling the pod is tedious, and the process is associated with drudgery. Also, field workers may sometimes sustain hand injuries in the process. For this reason, the pod is usually soaked for about 7 to 8 hours to soften the coat before manual dehulling (Das, 1999). Thus, there is the need to mechanize the dehulling process in order to address the problems associated with the manual method. In addition, the mechanized operation will help reduce drudgery associated with the manual method of dehulling the seed (Adejumo, 2012; Amin *et al.,* 2004; Adekunle *et al.,* 2008; Gupta and Das, 1999). It will also assist in reducing losses associated with dehulling and cleaning operations, thereby increasing the income of the local farmers who are engaged in the processing of the African oil bean seed (Correa *et al.,* 2007; Esref and Halil, 2007). Although, machines for dehulling different types of crop have been reported in literature (Adekunle *et al.,* 2008; Das, 1999; Yusuf and Sulaiman, 2000), there appears to be no reported study on the design of African oil bean dehuller. There is therefore the need to design a machine for the dehulling operation of African oil bean seed. The objective of this study is to design and simulate a dehuller for African oil bean seed.

2. Materials and Methods

2.1 Materials

Samples of the African oil bean seed (*Pentaclethra macrophylla*) were collected from Uselu Main Market in Benin City, Edo State, Nigeria. The seeds were then transported to the Kwara State University, Malete, Nigeria for experimentation. Manual cleaning method was used to remove foreign materials such as broken and immature seeds, stones, tree branches, leaves and sand from the seeds ((Fadeyibi and Osunde, 2012). The initial moisture content of the African oil bean seed was determined using the air circulated oven method and found to be 15.16% (db).

2.2 Design Considerations

Some relevant physical and mechanical proprieties of African oil bean seed were taken into consideration in this study. This was based on the available data reported for the physical and mechanical properties of seed in literature. Thus, the breadth (37.89 mm), volumetric flow rate (2.8 m^3/s), moisture content (15.16 %), angle of repose (32^o) and bulk density (0.588 g/cm^3), rupture force (1.12 kN), toughness (1.783 J), rupture stress 7.4 N/mm^2 and static coefficient of friction (0.3) at a moisture content of 15.16 % (db) were considered (Asoegu et al., 2006; Aremu *et al.*, 2014). The seed was conditioned to 15.16% moisture content using the method reported by Fadeyibi *et al.* (2012), and the physical and mechanical properties of the seed were used essentially in the design analysis.

2.3 Design Analysis

2.3.1 Hopper Volume

Hopper of the African oil bean dehuller was designed with its inlet and outlet diameters assumed, based on the study of existing hopper design, to be 256 mm and 90 mm, respectively. The procedure requires that the slant height of the hopper makes an angle slightly above 32^o (angle of repose of the African oil bean seed considered) (Fadeyibi *et al*., 2014). This forms a cone shaped hopper (Figure 2) with an assumed height of 300 mm, which is enough to ease the flow of the seeds into the barrel housing the dehulling unit. Equation (1) is used to compute the hopper volume.

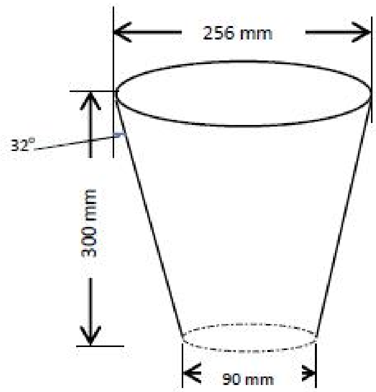

Figure 2: Hopper

$$V_h = \frac{1}{3}\pi(R^2 - r^2)h \quad (1)$$

where: V_h = hopper volume (mm^3), R = outer radius of the hopper (mm) = 128 mm, r = Inner radius of the hopper (mm) = 45 mm, h = Height of the hopper = 300 mm

Thus,

$$V_h = \frac{1}{3}\pi(128^2 - 45^2) \times 300$$

$$V_h = 4511598 \text{ mm}^3 = 0.004512 \text{ m}^3$$

Therefore the volume of the hopper was 0.004512 m^3

2.3.2 Barrel Volume

Barrel is a cylindrical drum which houses the dehulling unit of the machine (Nwakire *et al.,* 2011; Yusuf and Sulaiman, 2000). This was a horizontal hollow circular drum (Figure 3), with a length of 560 mm and a diameter of 90 mm, designed to dehull the African oil been seed to a capacity of 0.02 kg/mm^2 in a single pass. The dehulling mechanism is a spindle running through the entire length of the drum. The seeds are dehulled with the help of the flighted screws, which engage the pods, as the spindle rotates across its axis. The volume of the barrel was computed according to the expression in Equation (2) (Sudajan *et al.,* 2002).

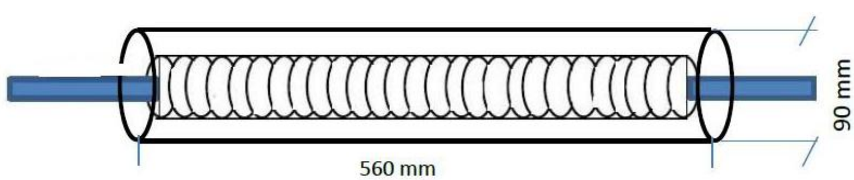

Figure 3: Barrel housing the spindle

$$V_b = \pi r^2 h \quad (2)$$

where: V_b = barrel volume (mm^3), r = base radius of the barrel (mm)
Thus,

$$V_b = \pi \times 45^2 \times 560$$
$$V_b = 3563028 \text{ mm}^3$$

Therefore, the volume of the used was 3563028 mm^3

2.3.3 Belt and Pulley arrangement

Consider a flat belt pulley arrangement showing the tensions in tight (T_1) and slack (T_2) sides in Figure 4. Notice that T_1 is positioned at the lower side so as to avoid sagging and wiping of the belt, which may subsequently cause a decrease in the wrap angle during a horizontal drive (Norton, 2006; Motto, 2004). The centre distance (c) between the driver and driven pulley was assumed to be 750 mm to prevent the belt from vibrating perpendicular to the direction of the motion, which may happen if the distance is too large or small, and subsequent creeping due to its elastic behavior during motion (Norton, 2006). Also, it is assumed that the driven pulley will rotate as one-third of the speed of the driver pulley so as to ensure that the lap angle is high enough to cause minimum tension on the slack side. Consequently, in this design, the diameter of the driven and the driver pulleys were therefore taken to be 90 mm and 30 mm, respectively. The drive provides power needed to rotate the spindle and to dehull the African oil bean seed. The driven pulley is positioned by means of a bearing to the shaft, while the driver pulley is attached to the electric motor bolted to the frame.

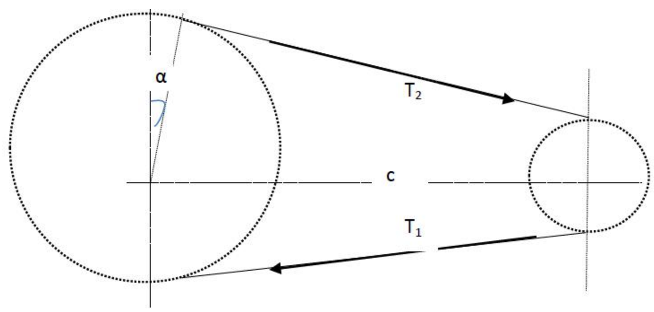

Figure 4: Pulley belt arrangement

Considering the rupture force of the African oil bean seed at 15.16 % moisture content as the maximum force required to dehulling, then tension on the tight belt was 1.12 kN. Assuming a flat-belt drive, the ratio of friction tensions is given in Equation (3):

$$\frac{T_1}{T_2} = e^{\mu\theta} \tag{3}$$

where: $\mathrm{T_1} = 1.12\ \mathrm{kN}$, $\mu = \text{Coefficient of friction between the belt and pulley} = 0.3$ (this corresponds to the value considered for the seed) $\alpha = \text{angle of wrap (degree)}$, $\theta = \text{angle of lap} = 180 - 2\alpha$

Thus, for an open v-belt drive, the angle of wrap is computed as follows (Khurmi and Gupta, 2004):

$$\sin\alpha = \frac{d_{1}{}_{-}d_2}{c}$$

$$\alpha = \sin^{-1}\left[\frac{90 - 30}{750}\right] = 4.59° \text{ (0.08 radian)}$$

But, $\theta = 180 - 2\alpha = 180 - 2 \times 4.59 = 170.82°$ (2.98 radian)

Recall and Applying Equation (3), then:

$$\frac{1120}{\mathrm{T}_2} = e^{0.3\times 2.98}$$

$$\mathrm{T}_2 = \frac{1120}{e^{(0.3\times 2.98)}} = 458.09 \text{ N}$$

Hence, based on this design, the tensions on the tight and the slack sides of the pulley are 1120 N and 458.09 N, respectively.

2.3.4 Determination of belt length

Belt length (for open belt drive) is obtained from the expression in Equation (4) (Motto, 2004).

$$L = 2c + \frac{\pi}{2}(d_1 + d_2) + \frac{(d_1 - d_2)^2}{4c} \tag{4}$$

where: L = required belt length (mm), c = Pulley center distance = 750 mm, d_2 = Driven pulley diameter = 90 mm, d_1 = Driver pulley diameter = 30 mm

$$L = 2 \times 0.75 + \frac{\pi}{2}(90 + 30) + \frac{(90 - 30)^2}{4 \times 750}$$

$$L = 1689.7 \text{ mm}$$

Hence, a flat belt of length 1690 mm approximately is used in this design.

2.3.5 Blower Design

An axial flow fan, which blows air parallel to the axis of rotation of the spindle and allows for through air circulation, was used to move air across the dehulling unit. Assume the blade length of 100 mm and blade width of 30 mm, the velocity of air circulation was computed from the expression in Equation (5) (Patankar and Suhas, 1990; Yisa and Fadeyibi, 2018).

$$C_a = \frac{\pi D N}{60} \tag{5}$$

$$Q = lwC_a$$

where, C_a = peripheral speed of the blade (m/s), Q = actual volume of air delivered across the dehulling unit (mm^3), D = diameter of the spindle (mm), N = speed of the blower (rpm), l = length of the blade (100 mm), w = width of the blade (30 mm).

Thus, with a spindle diameter of 20 mm and a blower speed of 150 rpm, the air velocity required to blow away the chaff or clean the dehulled seeds is computed as follows:

$$C_a = \frac{\pi \times 0.020 \times 150}{60} = 0.1571 \text{ m/s}$$

Hence, the actual volume capacity of air delivered across the dehulling unit is computed as follows:

$$Q = 0.1 \times 0.03 \times 0.1571$$

$$Q = 0.0005 \text{ m}^3\text{/s}$$

$$Q = 0.5 \times 60 = 30 \text{ L/min}$$

According to Jang *et al.* (2011), the blower with flow capacity in the range of 20-40 litres per minute is sufficient for lighter operations. Hence, in this case, since 30 L/min falls within the stated limit, the designed blower is satisfactory.

2.3.6 Selection of Key

Keys design is essential to help secure the hub and shaft so as to prevent relative movement between a power transmitting shaft and the driven pulley. From the table of proportion of standards and parallel rectangular keys, the key with a cross section dimension of width (w) = 8 mm, thickness (t) = 7 mm and a shear stress of 113 kN/m^2 was used (Khurmi and Gupta, 2004). Thus, the length of the key is computed from Equation (6).

$$\tau = lwt\delta \tag{6}$$

where: τ = Torque transmitted by shaft = 100.8 Nmm, l= required length of the key, w = width of key = 8 mm = 0.008 m, t = thickness of the key = 7 mm = 0.007 m; δ = shear stress of the material of key = 113 kN/m^2

$$l = \frac{100.8}{0.008 \times 0.007 \times 113000} = 0.0159 \text{ m}$$

Hence, according to the dimension and tolerance of metric keyways for parallel rectangular keys (BS 4235-1: 1972), a key of dimension $8 \text{ mm} \times 7\text{mm} \times 15 \text{ mm}$ will firmly secure the shaft and driven pulley in position.

2.3.7 Dehulling Unit

The machine dehulling unit was housed in the barrel and this is made up of beater, spindle and shaft (Yusuf and Sulaiman, 2000). The beater and spindle were attached to the shaft and together are responsible for removing the African oil bean seeds from the pods. The spindle is made of 30 mm gauge mild steel welded on the shaft to form equal flight, as shown in Figure 5.

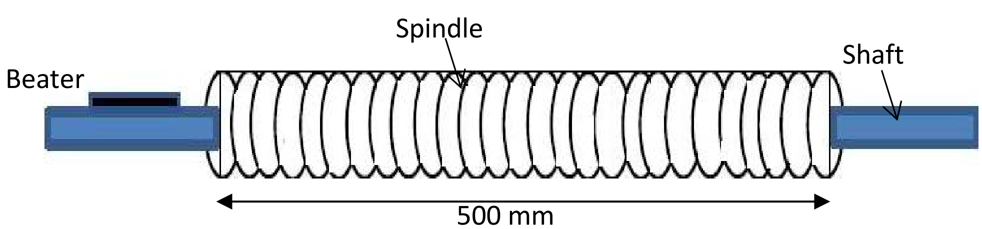

Figure 5: Dehulling Unit

Shaft diameter was determined using Equation (7) as is given by Khurmi and Gupta (2004). The design was based on the assumption that the bending and torsional stresses on the shaft are nearly uniform (Motto, 2004) such that the combined shock and fatigue factor for bending and torsion are 1.5 and 1.0, respectively.

$$d^3 = \frac{16}{\pi\tau_{mx}}\sqrt{[(k_bM_b)^2 + (k_tM_t)^2]} \tag{7}$$

where, d = shaft diameter required, τ_{mx}= max allowable shear stress on the shaft = 42 x 10^3 N/m^2 (Khurmi and Gupta, 2004), k_b = combined shock and fatigue factor for bending = 1.5, k_t= combined shock and fatigue factor for torsion = 1.0, M_b = bending moment of belt drive on shaft = 55.74 Nm (which is a function of the rupture force of the seed, weight of the spindle, the shaft speed and the shaft length), M_t = torsional moment on the shaft = 59.5 Nm (Khurmi and Gupta, 2004).

$$d^3 = \frac{16}{\pi \times 42000}\sqrt{[(1.5 \times 55.74)^2 + (1 \times 59.5)^2]}$$

$$\mathrm{d} = 23.2\mathrm{mm}$$

Thus, allowing a factor of safety of 5%, the actual diameter of the shaft is

$$\mathrm{d} = 23.2 \times 1.05 \approx 25 \text{ mm}$$

2.3.8 Power Requirement

The power required for motor selection will depend on the individual power consumed by the dehulling and the blower units of the machine. Thus, the sum of the individual power is the power required to operate the machine.

Power used for dehulling: According to Khurmi and Gupta (2004), the power required by the dehulling unit is computed from Equation (8).

$$P = \omega\tau = \frac{2\pi N\tau}{60} \qquad (8)$$

where: N= speed of the driver pulley (rpm) , τ= Torque of the driver pulley on the shaft (N.mm).

But, Norton (2006) reported that, for light belt drive of most agricultural machines, the velocity of the driven and the driver pulleys is equal. Based on this, the speed ratio between the two pulleys is expressed in Equation (9). However, most electric motors have speed rating of 1445 rpm, and this was taken as the the speed of the driver pulley. Thus, the speed of the driven pulley is computed as follows:

$$\frac{N_1}{N_2} = \frac{d_2}{d_1} \qquad (9)$$

$$v = \frac{\pi N_1 d_1}{60}$$

$$N_1 = \frac{N_2 d_2}{d_1} = \frac{1445 \times 30}{90} = 481.67 \text{ rpm}$$

Hence, the speed of the driver pulley is approximately 482 rpm

Also, the torque produced by the driver pulley is computed as follows:

$$\tau = \frac{T_1 d_1}{2}$$

$$\tau = \frac{1120 \times 0.09}{2} = 100.8 \text{ Nm}$$

Thus, from Equation (8), the power required for dehulling alone is,

$$\mathrm{P} = \omega\tau = \frac{2\pi \times 482}{60}$$

$$\mathrm{P} = \frac{2\pi \times 482}{60} = 50.48 \text{ Watts}$$

Power used by the blower: Ideal power consumption for a blower (without losses) is expressed in Equation (9) (Patankar and Suhas, 1990).

$$P_i = \partial p \, q \quad (9)$$

where, $P_i =$ ideal power consumption (W), ∂p = Total pressure of the blower (Pa) = 575 Pa, q = volumetric flow rate of the African oil bean seed = 2.8 m^3/s (obtained from previous investigation), $\mu =$ Blower efficiency.

However, the blower efficiency (μ) is computed from Equation (10)

$$\mu = \mu_f \mu_b \mu_m \quad (10)$$

where: $\mu_f =$ Blower efficiency (this is generally independent of air density for power of more than 10 kW) = 0.95, $\mu_b =$ Belt Efficiency (for power of more than 10 kW) = 0.98, $\mu_m =$ Motor Efficiency (for power of more than 10 kW) = 0.99.

$$\text{Thus, } \mu = 0.95 \times 0.98 \times 0.99 = 0.92$$

But, Equation (11) is used to compute the power used by the blower as follows,

$$P_n = \frac{\partial p \, q}{\mu} \quad (11)$$

$$P_n = \frac{2.8 \times 575}{0.92} = 1750 \text{ W} = 1.75 \text{ kW}$$

Therefore,

Total power = Power required for dehulling + Power used for blower

$$P_k = 50.48 + 1750 = 1800.48 \text{ W}$$

However, the design power contribution is computed by multiplying the service factor by the nominal power as follows:

$$P = P_k \times f_s$$

where: f_s = service factor (assumed 20 % power loss from other components due to friction).

$$P = 1800.48 \times 1.2$$

$$\therefore \quad P = 2160.56 \text{ W or } 2.90 \text{ hp}$$

Therefore, a 3 HP single phase electric motor, with a design speed of 1445 rpm, is selected to power the dehuller.

2.4 Machine Simulation

The machine was simulated using Solid Works Design Package (ver. 11.0) by Computational Fluid Dynamic (CFD) method. The CFD uses numerical analysis and data structures to solve and analyze the problems that involve fluid flows and also predict the pressure field induced by the interaction of the machine members. In theory, the finite volume method (FVM) uses the CFD code governed by partial differential equation, typically the Navier-Stokes Equation for the single flow behavior of the machine, as expressed in Equation (12) (Fadeyibi *et al.,* 2016; Patankar and Suhas, 1990). In this investigation, a stream of air at a flow rate of 2.8 m^3/s (as stated in the design consideration) was passed hypothetically into the dehuller for 15 seconds, and the flow behavior of the dehulled product

was observed with respect to the motor torque, linear displacement and angular velocity as a function of the time of machine operation.

$$\frac{\partial}{\partial t}\iiint Qdv + \iint Fdv = 0 \quad (12)$$

where: Q = vector of conserved variable (kg/s), F = vector of fluxes (N), V = volume of control volume element (mm^3), A = surface area of the control volume element (mm^2 The time baundary condition was $0 < \partial t < 15$ seconds.

3. Results and Discussion

3.1 Machine description

Machine drawing of the African oil bean dehuller is shown as a part drawing of the barrel and separator of the dehuller (Figure 6), orthographic projection (Figure 7), exploded view of the dehuller component parts (Figure 8), frame housing (Figure 9) and isometric view (Figure 10).

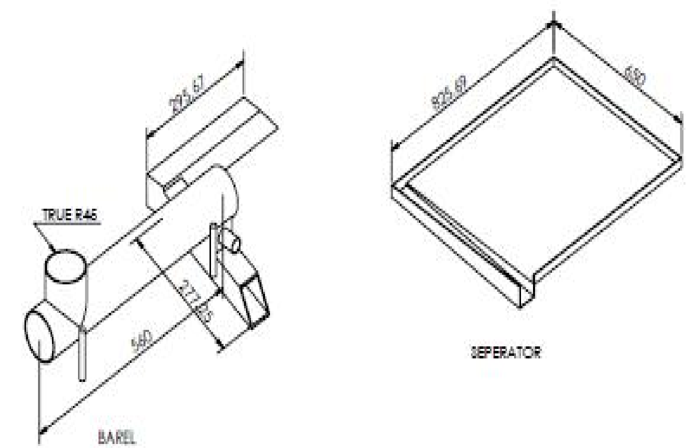

Figure 6: Barrel and separator of the dehuller

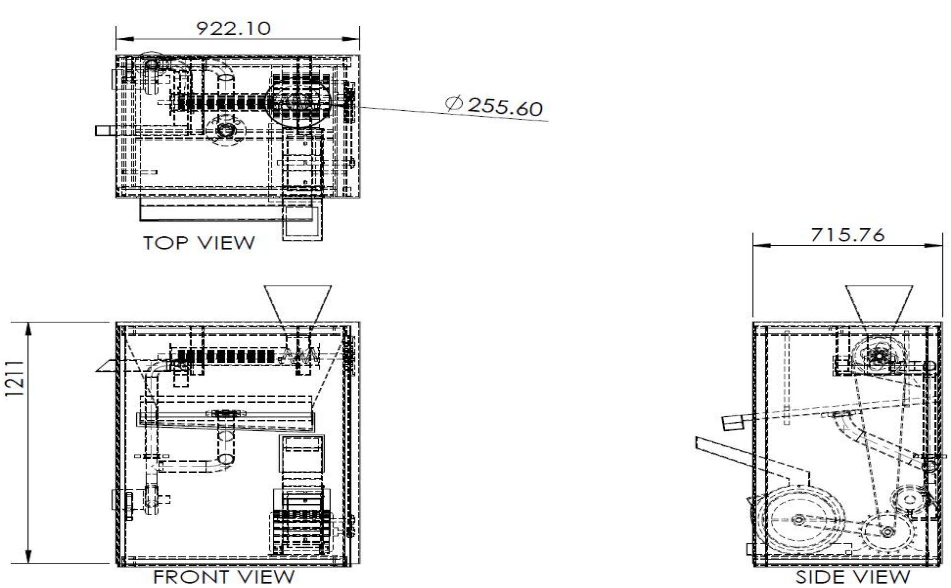

Figure 7: Orthographic projection of the dehuller

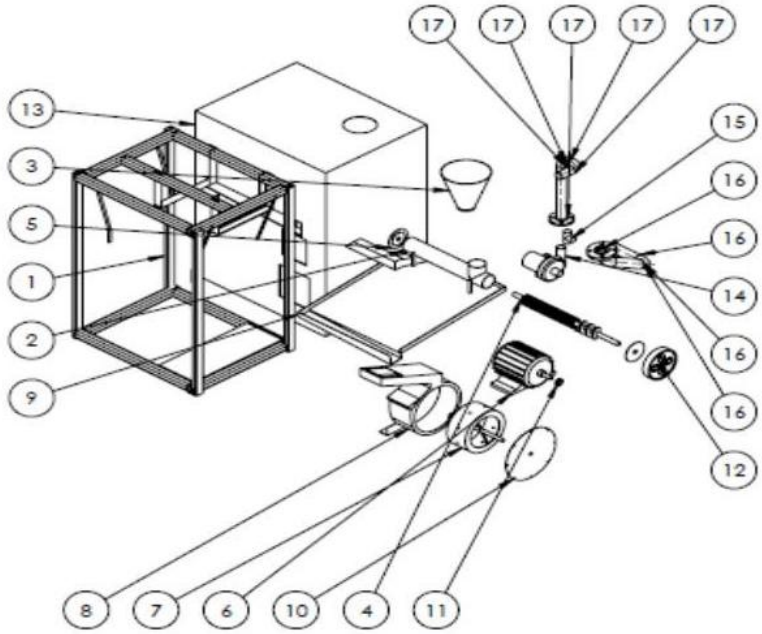

Figure 8: Exploded view of the dehuller (1-Frame, 2-Barrel, 3-Hopper, 4-Shaft, 5 Barel cover, 6-Electric motor, 7-Polisher part I, 8-polisher part II, 9-Discharge way, 10-Blower cover, 11-Driven Pulley, 12-Drver pulley, 13-Frame Housing, 14-Blower, 15-T Pipe, 16-Pipe 1-Asbestors, 17- Pipe 2-Asbestors)

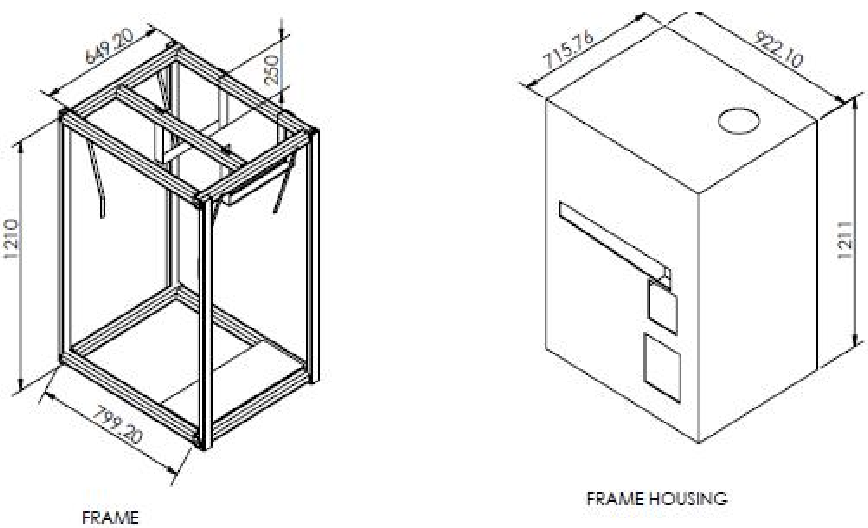

Figure 9: Frame and frame housing

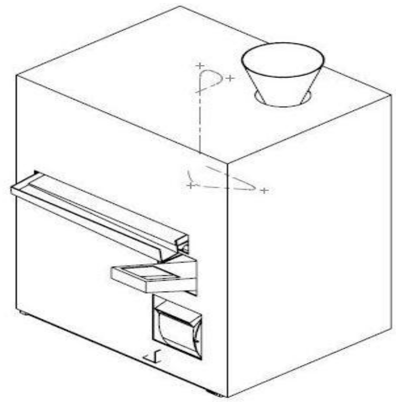

Figure 10: Isometric view of the Dehuller

The major components consist of the following: the hopper, dehulling chamber, dehulling disc and the sieve, cleaning chamber and the belt guard. The hopper was made up of mild steel. The opening allows the African oil bean seeds into the dehulling chamber. The dehulling chamber consists of dehulling shaft and the barrel which are powered by an electric motor. The dehulling shaft is made up of mild steel; the dehulling shaft is incorporated in the barrel. The machine is mounted on a frame that is made up of angle iron, the whole unit and rest on the frame. The component parts of the machine are as follows:

i. Hopper unit: This structure is the unit in which material to be dehulled is regulated and channeled into the dehulling chamber. It is made of 20 gauge mild steel metal sheet. It is circular in shape tapper towards the dehulling mechanism for easy flow of the material by gravity.
ii. Frame: it is the main support for the machine and it will be made of angle iron 300 x 300 mm and 2 mm thickness.
iii. Dehulling Unit: it is made up of beater and screws which are mounted on the shaft and inside the barrel the shaft received transmission from the pulley for dehulling.
iv. The blower: It separates the seed from the chaff after dehulling at air volume capacity of 30 L/min. The blower driven rate is based on the weight, shape and size of the African oil bean seeds.
v. Seed Discharge Outlet: This serves as the collection outlet for the dehulled African oil bean seeds. The seed fall under gravity from the dehulling chamber into a collection tray underneath.

3.2 Principle of Operation of Machine

The working principle of machine was based on the principle of energy absorbed by seed as a result of impact (collision) between the seed and dehulling shaft which cause cracking and removed the seed coat. Whole African oil bean seeds were fed into the machine through the hopper which opens directly into the dehulling unit. The whole seeds were supplied with initial velocity by the screw as the shaft rotates anticlockwise, in order to enhance the collision of the beating unit to cause of the breakage of the pod and the removal of the chaff from the dehulled seed and the chaffs were blown out of the blower. The machine was driven by a single phase electric motor of 3 HP at a speed of 1445 rpm.

3.3 Machine Simulation

The simulation using the CFD has been done in order to study the dehulling behavior of the machine during operation. The result from the machine simulation and dehulling operation are shown in Figures (11) to (13). Simulation of the African oil, beans dehuller was performed using the

computational fluid dynamics method (cfd). The effects of time of machine operation on motor torque, angular velocity and linear displacement were hypothetically being represented in Figures (11) to (13), respectively. It can be seen that the motor torque was inconsistent throughout machine operation (Figure 11). The motor torque was a function of the overall weight of the motor with respect to the centre to centre distance between the driver and driven pulley arrangement. As the machine commences operation, the angular velocity was higher, but this progressively decreases with time of machine operation (Figure 12). This is probably because of the decrease in the viscous effect of the internal wall which causes the air stream flow to slow down with a resultant drop in the relative angular velocity to the surface (Cengel and Cimbala, 2006). A similar result has been reported by Lim *et al.* (2016) in their work on performance evaluation and cdf multiphase modeling of multistage Jatropha fruit dehulling machine. The dehulling operation was faster in the first few minutes of operation since the dehulling unit was engaged with increasing acceleration. Therefore, loading the African oil bean seeds near the side wall may not yield the optimal dehulling.

Although, in practice this might not be true, but with adequate compliance to detail in design one would expect performance to be higher at the first instance of machine operation. The relationship between the linear displacement and time of machine operation is a periodic series, which obeyed both sine and cosine functions, as shown in Figure 13. The linear movement of the shaft was shown to be uniform at the beginning, middle and final stages of the dehulling operation. This may be due to the differential movement of the air stream across the dehulling unit. Theoretically, the kinetic energy must decrease when the air passes through a diverging portion to achieve stability with an increase in pressure (Cengel and Cimbala, 2006). It is possible that the momentum of the shaft was sustained throughout the journey, which could be responsible for the equal half speed generated in each circle of the linear motion. This implies that the machine is practicable and has potential to dehull African oil bean seeds. The performance of the machine is likely to decrease with time of machine operation, and this of course is expected for its operation even in a worst case scenario.

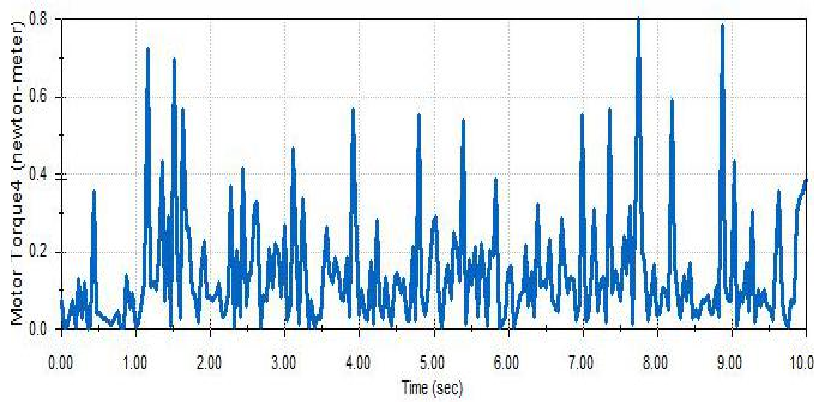

Figure 11: Effect of time of operation on motor torque

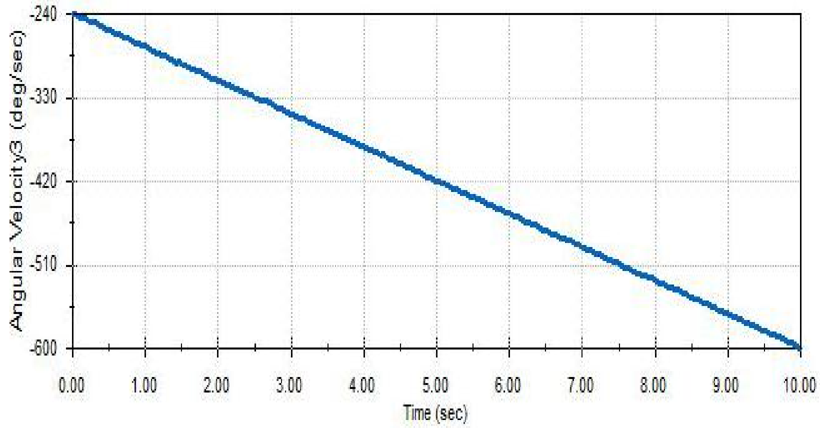

Figure 12: Effect of time of operation on angular velocity

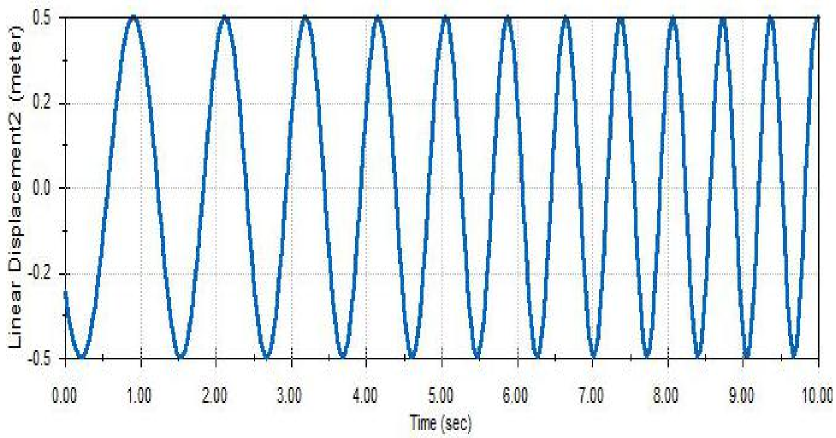

Figure 13: Effect of time of operation on linear displacement

4. Conclusion

African oil bean seeds dehuller has been successfully designed to be operated using a 3 HP single phase electric motor. From the simulation result, it was observed that the relationship between the linear displacement and time of machine operation is a periodic series, which obeyed both sine and cosine functions . The angular velocity was higher as the machine commences operation, but this progressively decreases with time of machine operation. The motor torque was found to be inconsistent throughout machine operation. Consequently, the machine is practicable with performance likely to decrease with time of machine operation. However, with adequate compliance to detail in design one would expect performance of the machine to be high in concrete reality.

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